Is the polarized light flavor sea-quark asymmetric? [†]

Toshiyuki MORII [‡] and Teruya YAMANISHI*, [§]

Faculty of Human Development, Kobe University, Nada, Kobe 657-8501, Japan
*Department of Management Sciences, Fukui University of Technology, Gakuen, Fukui 910-8505, Japan

abstract

Simple formulas on $\Delta\bar{d}(x) - \Delta\bar{u}(x)$ are proposed for extracting their values from polarized deep-inelastic semi-inclusive data. The present SMC and HERMES data suggest that $\Delta\bar{d}(x) - \Delta\bar{u}(x)$ is slightly negative, though the precision of the data is not enough for confirming it.

1   Introduction

Since the NMC experiment in 1991[1], which precisely measured the structure functions of the proton and neutron, $F_2^p(x)$ and $F_2^n(x)$, for a wide region of Bjorken's x, it has been realized that the Gottfried sum rule[2] is violeted and the light sea-quark distributions, $\bar{u}(x)$ and $\bar{d}(x)$, are asymmetric. A considerable excess of the $\bar{d}$ quark density relative to the $\bar{u}$ quark density was seen. The same result was confirmed by the E866 experiment which measured the cross section ratio of the Drell-Yan processes, $\sigma(p+d)/\sigma(p+p)$, though the violation of the Gottfried sum rule is smaller than reported by the NMC. Now, study on the origin of the flavor asymmetry of light sea–quarks has been a challenging subject in particle and nuclear physics because it is closely related to the dynamics of nonperturbative QCD[4]. Although the most widely accepted idea to understand it is the meson cloud model, many discussions are still under going with several approaches such as chiral quark model, Skyrme model, Pauli blocking effects, etc.[5].

However, what is going on with the polarized case, $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$? In these years, measurement of the polarized structure function of the nucleon in polarized deep–inelastic scatterings have shown that the nucleon spin is carried by quarks a little and the strange sea–quark is negatively polarized in quite large. The results were not anticipated by conventional theories and often referred as '*the proton spin crisis*'[6]. By using many data with high precision on the polarized structure functions of the proton, neutron and deuteron accumulated so far, good parametrization models of polarized parton distribution functions have been proposed at the next–to–leading order(NLO) of QCD[7]. The behavior of polarized valence u and d quarks has been well–known from such analyses. However, the knowledge of polarized sea–quarks and gluons is still poor. Although people usually assume the symmetric light sea–quark polarized distribution, i.e. $\Delta\bar{u}(x) = \Delta\bar{d}(x)$, in analyzing the polarized structure functions of nucleons, there is no physical ground of such an assumption. In order to understand the

---

[†]Talk presented by T. Morii at the Circum-Pan-Pacific RIKEN Symposium on "High Energy Spin Physics" (RIKEN, Wako, Japan, Nov. 3-6, 1999).

[‡]E-mail address: morii@kobe-u.ac.jp

[§]E-mail address: yamanisi@rcnp.osaka-u.ac.jp

nucleon spin structure, it is very important to know if the light sea–quark flavor symmetry is broken even for polarized distributions and to determine how $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ behave in the nucleon. Related to these subjects, it is interesting to know that even if we start with the symmetric distributions for the polarized light sea–quarks, $\Delta\bar{u} = \Delta\bar{d}$, at an initial Q_0^2, the symmetry can be violated for higher Q^2 regions, if the polarized distributions are perturbatively evolved in NLO calculations of QCD[8]. In addition, some people have estimated the amount of its violation at an initial Q_0^2 using some effective models. However, their results do not agree with each other[9, 10]. Therefore, it is interesting to extract the value of $\Delta\bar{d}(x) - \Delta\bar{u}(x)$ from the experimental data and test the flavor symmetry of $\Delta\bar{d}(x)$ and $\Delta\bar{u}(x)$ experimentally.

Recently, using longitudinal polarized lepton beams and longitudinal polarized fixed targets, SMC group at CERN[11] and HERMES group at DESY[12, 13] observed the cross sections of the following semi–inclusive processes,

$$\vec{l} + \vec{N} \to l' + h + X \ , \tag{1}$$

and obtained the data on spin asymmetries for proton, deuteron and ^{3}He targets, where h is a created charged hadron or one of $\pi^\pm$, $K^\pm$, p and $\bar{p}$. A created hadron depends on the flavor of a parent quark and thus properly combining these data it is possible to decompose polarized quark distributions into the ones with individual flavor[14]. These data provide a good material to test the light flavor symmetry of polarized sea–quark distributions and it might be timely to test the symmetry by using the present data.

2 Simple formulas of $\Delta\bar{d}(x) - \Delta\bar{u}(x)$

In this letter, we propose new formulas for extracting a difference, $\Delta\bar{d} - \Delta\bar{u}$, from the data of the above–mentioned semi–inclusive processes and estimate the value of it from the present data in order to test if the light flavor symmetry of polarized sea–quark distributions is originally violated.

Let us start with the semi–inclusive asymmetry for the process of eq.(1) with proton targets, which is written by[11]

$$A_{1p}^h(x, Q^2) \ = \frac{\sum_{q,H} \ e_q^2 \ \{\Delta q(x, Q^2) \ D_q^H(Q^2) + \Delta\bar{q}(x, Q^2) \ D_{\bar{q}}^H(Q^2)\}}{\sum_{q,H} \ e_q^2 \ \{q(x, Q^2) \ D_q^H(Q^2) + \bar{q}(x, Q^2) \ D_{\bar{q}}^H(Q^2)\}} \ \times \{1 + R(x, Q^2)\}, \tag{2}$$

in the leading order(LO) of QCD[15], where $\Delta q(x, Q^2)$ $(\Delta\bar{q}(x, Q^2))$ and $q(x, Q^2)$ $(\bar{q}(x, Q^2))$ are the spin–dependent and spin–independent quark distribution functions at some values of x and Q^2, respectively, and $R(x, Q^2)$ is a ratio of the absorption cross section of longitudinally and transversely polarized virtual photons by the nucleon, $R(x, Q^2) = \sigma_L/\sigma_T$. $D_q^H(Q^2)$ is given by integration of the fragmentation function, $D_q^H(z, Q^2)$, over the measured kinematical region of z, i.e. $D_q^H(Q^2) = \int_{z_{min}}^1 dz \ D_q^H(z, Q^2)$, where $D_q^H(z, Q^2)$ represents the probability of producing a hadron H carrying momentum fraction z at some Q^2 from a struck quark with flavor q. h is the observed hadron concerned with here. When h is h^+, the fragmentation function of, for example, u–quark decaying into h^+ is given by

$$D_u^{h^+}(z, Q^2) = D_u^{\pi^+}(z, Q^2) + D_u^{K^+}(z, Q^2) + D_u^p(z, Q^2) \ , \tag{3}$$

because h^+ is dominantly composed of π^+, K^+ and p. Assuming the reflection symmetry along the V–spin axis, the isospin symmetry and charge conjugation invariance of the fragmentation functions, many fragmentation functions can be classified into the following 6 functions[4],

$$D \equiv D_u^{\pi^+} = D_{\bar{d}}^{\pi^+} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^-} \quad ,$$

$$\widetilde{D} \equiv D_d^{\pi^+} = D_{\bar{u}}^{\pi^+} = D_u^{\pi^-} = D_{\bar{d}}^{\pi^-} = D_s^{\pi^+} = D_{\bar{s}}^{\pi^+} = D_s^{\pi^-} = D_{\bar{s}}^{\pi^-} \quad ,$$

$$D^K \equiv D_u^{K^+} = D_{\bar{s}}^{K^+} = D_{\bar{u}}^{K^-} = D_s^{K^-} \quad ,$$

$$\widetilde{D^K} \equiv D_d^{K^+} = D_s^{K^+} = D_{\bar{u}}^{K^+} = D_{\bar{d}}^{K^+} = D_u^{K^-} = D_d^{K^-} = D_{\bar{d}}^{K^-} = D_{\bar{s}}^{K^-} \quad ,$$

$$D^p \equiv D_u^p = D_d^p = D_{\bar{u}}^{\bar{p}} = D_{\bar{d}}^{\bar{p}} \quad ,$$

$$\widetilde{D^p} \equiv D_s^p = D_{\bar{u}}^p = D_{\bar{d}}^p = D_{\bar{s}}^p = D_u^{\bar{p}} = D_d^{\bar{p}} = D_s^{\bar{p}} = D_{\bar{s}}^{\bar{p}} \quad ,$$

(4)

where D^H and $\widetilde{D^H}$ are called favored and unfavored fragmentation functions, respectively. Here we follow the commonly taken assumption on the fragmentation functions, for simplicity.

Now, we can rewrite eq.(2) as

$$\sum_{q,H} e_q^2 \left\{ \Delta q(x, Q^2)\, D_q^H(Q^2) + \Delta\bar{q}(x, Q^2)\, D_{\bar{q}}^H(Q^2) \right\}$$

$$= \frac{A_{1p}^h(x, Q^2)\, [\sum_{q,H} e_q^2\, \{q(x, Q^2)\, D_q^H(Q^2) + \bar{q}(x, Q^2)\, D_{\bar{q}}^H(Q^2)\}]}{\{1 + R(x, Q^2)\}}$$

$$= \Delta N_p^h(x, Q^2) \ , \tag{5}$$

where $\Delta N_p^h(x, Q^2)$ is reffered to the spin–dependent production processes of charged hadrons with proton targets. From a combination of $\Delta N_{p,n}^{h^+, h^-}(x, Q^2)$ for proton and neutron targets, we can obtain the following formula,

$$\Delta\bar{d}(x, Q^2) - \Delta\bar{u}(x, Q^2)$$

$$= \frac{\Delta N_p^{h^+}(x, Q^2) - \Delta N_n^{h^+}(x, Q^2) - \Delta N_p^{h^-}(x, Q^2) + \Delta N_n^{h^-}(x, Q^2)}{2\, I_1(Q^2)}$$

$$- \frac{\Delta N_p^{h^+}(x, Q^2) - \Delta N_n^{h^+}(x, Q^2) + \Delta N_p^{h^-}(x, Q^2) - \Delta N_n^{h^-}(x, Q^2)}{2\, I_2(Q^2)} \ , \tag{6}$$

where

$$I_1(Q^2) = 5D(Q^2) + 4D^K(Q^2) + 3D^p(Q^2) - 5\widetilde{D}(Q^2) - 4\widetilde{D^K}(Q^2) - 3\widetilde{D^p}(Q^2) \ ,$$

$$I_2(Q^2) = 3D(Q^2) + 4D^K(Q^2) + 3D^p(Q^2) + 3\widetilde{D}(Q^2) + 2\widetilde{D^K}(Q^2) + 3\widetilde{D^p}(Q^2) \ .$$

(7)

Furthermore, if one can specify the detected charged hadron in experiment, one can obtain more simplified formulas for the difference of polarized light sea–quark densities. For the case of semi–inclusive $\pi^\pm$–productions with proton and neutron targets, the difference can be written by

$$\Delta\bar{d}(x, Q^2) - \Delta\bar{u}(x, Q^2)$$

$$= \frac{1}{6\{D(Q^2) + \widetilde{D}(Q^2)\}} \times [\{J(Q^2) - 1\}\{\Delta N_p^{\pi^+}(x, Q^2) - \Delta N_n^{\pi^+}(x, Q^2)\} \tag{8}$$

$$-\{J(Q^2) + 1\}\{\Delta N_p^{\pi^-}(x, Q^2) - \Delta N_n^{\pi^-}(x, Q^2)\}] \,,$$

where $J(Q^2) = \frac{3(D(Q^2) + \widetilde{D}(Q^2))}{5(D(Q^2) - \widetilde{D}(Q^2))}$. Eqs.(6) and (8) are main results of this work. Based on these formulas, one can extract $\Delta \bar{d}(x, Q^2) - \Delta \bar{u}(x, Q^2)$ by using the values of $\Delta N_N^h(x, Q^2)$ which can be derived from experimental data of spin asymmetries $A_{1N}^h(x, Q^2)$, if the spin–independent quark distribution functions and fragmentation functions are well known.

3 Extraction of $\Delta \bar{d}(x) - \Delta \bar{u}(x)$ from semi-inclusive data

The remaining task is to numerically estimate the value of $\Delta \bar{d}(x, Q^2) - \Delta \bar{u}(x, Q^2)$ from the present semi–inclusive data in order to examine how these formulas are effective for testing the light flavor symmetry of polarized distributions. In this analysis, we use the parametrization of GRV98(LO)[16] for the unpolarized parton distribution being the $\bar{u}/\bar{d}$ asymmetric and the R1990 parametrization[17] for the ratio R in eq.(2). The fragmentation functions of eq.(4) are determined so as to fit well the EMC data[18] and by integrating them from $z_{min} = 0.2$ to 1, we have obtained $D^H(Q^2)$ and $\widetilde{D}^H(Q^2)$. At present, we have some data of $A_{1p}^{h^\pm}$ and $A_{1d}^{h^\pm}$ measured by the SMC group and also some data of $A_{1p}^{h^\pm}$, $A_{1^3He}^{h^\pm}$, $A_{1p}^{\pi^\pm}$ and $A_{1^3He}^{\pi^\pm}$ by the HERMES group. From these data, we can estimate the values of $\Delta \bar{d}(x, Q^2) - \Delta \bar{u}(x, Q^2)$ from eqs.(6) and (8) by using ΔN_N^h calculated from the data set of $(A_{1p}^{h^\pm}, A_{1d}^{h^\pm})$ by SMC and $(A_{1p}^{h^\pm}, A_{1^3He}^{h^\pm})$ and $(A_{1p}^{\pi^\pm}, A_{1^3He}^{\pi^\pm})$ by HERMES. Here, for the data of ^{3}He targets, the values of A_{1n}^h were derived from the data of $A_{1^3He}^h$ according to the way in ref.[13]. In the present analysis, we have neglected the Q^2 dependence being fixed as $Q_0^2 = 4\text{GeV}^2$ because no significant Q^2 dependence has been observed in this region in the spin asymmetry A_{1N} for inclusive data[19]. The results calculated from eqs.(6) and (8) are presented in fig.1. We have checked the model dependence of unpolarized quark distribution functions and found that the results are not sensitive to those models.

To examine the behavior of $\Delta \bar{d}(x) - \Delta \bar{u}(x)$ in more detail and to test the light flavor asymmetry of $\Delta \bar{d}(x)$ and $\Delta \bar{u}(x)$, we have parametrized it as

$$\Delta \bar{d}(x) - \Delta \bar{u}(x) = Cx^\alpha(\bar{d}(x) - \bar{u}(x)), \tag{9}$$

and determined the values of C and α from the χ^2–fit to the results presented in fig.1. The results were $C = -3.40(-3.87)$ and $\alpha = 0.567(0.525)$ for the GRV98(LO)[16](MRST98(LO)[20]) unpolarized distributions, while the values of χ^2/d.o.f. were 0.91(0.90) for GRV98(LO)(MRST98(LO)). $C < 0(\neq 0)$ is a remarkable result, suggesting an asymmetry of $\Delta \bar{d}(x)$ and $\Delta \bar{u}(x)$. It is interesting to note that the negative value of C is consistent with instanton interaction predictions[21]. Also, the similar result is indicated from the chiral quark soliton model[22]. However, it must be premature to lay stress on this result because of too large errors of the present data, though this result might suggest a violation of the polarized light flavor sea–quark symmetry. We urge to have more data with high precision to confirm this result.
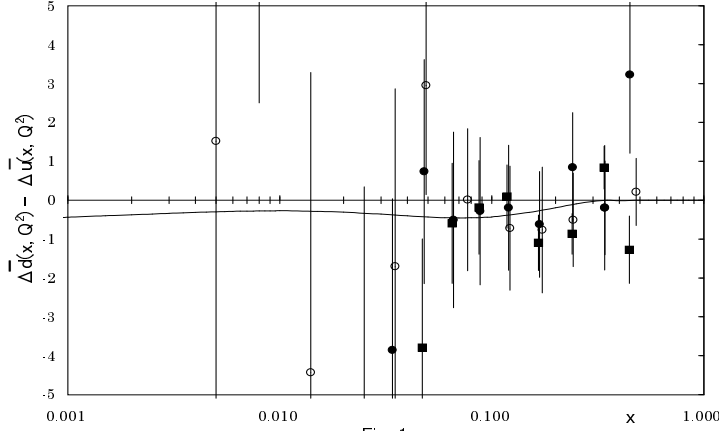
Figure 1: The x dependence of $\Delta\bar{d}(x, Q^2) - \Delta\bar{u}(x, Q^2)$ at $Q^2 = 4$ GeV^2 estimated by using the GRV98(LO) and R1990 parametrizations for the unpolarized quark distributions and ratio R, respectively. Marks indicated by the solid circle, open circle and solid square denote the results calculated from the data set of SMC data, HERMES data for charged hadron productions and HERMES data for charged pion productions, respectively. The solid line indicates the result of χ^2-fit by the parametrization of eq. (9).

Some comments are in order for the usefulness of our formulas: (i) Our formulas depend on the unpolarized parton distribution functions and the fragmentation functions. Unfortunately, some of them are poorly known at present. In addition, $\Delta N_{p(n)}^h$ depends on the semi–inclusive asymmetry, $A_{1p(n)}^h$, and contains some experimental errors. Therefore, it might be rather difficult to extract the exact value of $\Delta\bar{d}(x) - \Delta\bar{u}(x)$ from the present data. However, we believe that they must be quite useful for future experimental test of the polarized light sea-quark asymmetry if we have more precise data and good information on these functions. Our formulas are simple and can be easily tested in experiment. (ii) At present we see only asymmetries, $A_{1p(n)}^h$, in literature. However, if the precise experimental data on the polarized cross sections will be presented, then our formulas make more sense by replacing $A_{1p(n)}^h$ by the polarized cross sections themselves, where the unpolarized parton distributions and $R(x, Q^2)$ do not come in and we do not need to worry about their uncertainty.

4 Summary and discussion

In conclusion, we have proposed simple new formulas for extracting a difference of the polarized light sea–quark density, $\Delta\bar{d}(x) - \Delta\bar{u}(x)$, from polarized deep–inelastic semi–inclusive data and numerically estimated it using these formulas from the present experimental data for semi–inclusive processes. Unfortunately, the precision of the present data is not enough for extracting an exact value of the difference, $\Delta\bar{d}(x) - \Delta\bar{u}(x)$, and unambiguously testing the polarized light flavor sea–quark asymmetry. However, the HERMES group is now measuring semi–inclusive processes by using a new detector called RICH which can identify each of charged particles over a wide kinematical range and these data of charged pions with high statistics are expected to allow us to test more clearly the asymmetry of polarized light flavor sea–quark densities.

Another interesting way to study the asymmetry of $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ is the Drell–Yan process for polarized proton/deuteron–polarized proton collisions[23]. The process provides informations on the raito of $\Delta\bar{u}(x)/\Delta\bar{d}(x)$ and thus it is complementary to our processes.

Acknowledgements

References

[1] P. Amaudruz et al., NM Collab., Phys. Rev. Lett. **66** 2712 (1991).

[2] K. Gottfried, Phys. Rev. Lett. **18** 1174 (1967).

[3] E. A. Hawker et al., E866/NuSea Collab., Phys. Rev. Lett. **80** 3715 (1998).

[4] For a recent review see: S. Kumano, Phys. Rep. **303** 183 (1998).

[5] For example: F. M. Steffens and A. W. Thomas, Phys. Rev. **C55** 900 (1997).

[6] For a recent review see: B. Lampe and E. Reya, preprint hep–ph/9810270 (1998).

[7] For examples: M. Glück, E. Reya, M. Stratmann, and W. Vogelsang, Phys. Rev. **D53** 4775 (1996); T. Gehrmann and W. J. Stirling, Phys. Rev. **D53** 6100 (1996); E. Leader, A. V. Sidorov, and D. B. Stamenov, Phys. Rev. **D58** 114028 (1998).

[8] M. Stratmann, A. Weber, and W. Vogelsang, Phys. Rev. **D53** 138 (1996).

[9] R. J. Fries and A. Schäfer, Phys. Lett. **B443** 40 (1998).

[10] B. Dressler et al., *Flavor asymmetry of polarized and unpolarized sea quark distributions in the large–N_c limit*, talk given at the 11th International Conference on Problems of Quantum Field Theory, Dubna, Russia (1998), hep-ph/9809487.

[11] B. Adeva et al., SM Collab., Phys. Lett. **B420** 180 (1998).

[12] A. Simon, HERMES Internal Note 98–054, *Results and Perspectives in Particle Physics*, talk given at the XIIth Rencontre de Physique de la Vallée d'Aoste, La Thuile, Italy (1998).

[13] M. A. Funk, Ph. D. Thesis, DESY–THESIS–1998-017 (1998).

[14] L. L. Frankfurt et al., Phys. Lett. **B230** 141 (1989); F. E. Close and R. G. Milner, Phys. Rev. **D44** 3691 (1991); J. M. Niczyporuk and E. E. W. Bruins, Phys. Rev. **D58** 091501 (1998).

[15] We consider eq.(2) in the LO of QCD in order to simplify the analysis. For the NLO analysis, the factorized form of eq.(2) in terms of x and z variables cannot be realized, where we have double convolution integrals for parton distributions, fragmentation functions and Wilson coefficents as discussed by G. Altarelli, R. K. Ellis, G. Martinelli, and S. -Y. Pi, Nucl. Phys. **B160** 301 (1979); W. Furmanski and R. Petronzio, Z. Phys. **C11** 293 (1982). Furthermore, although in the NLO analysis we need a fragmentation function of NLO, we do not have good knowledge of it at present.

[16] M. Glück, E. Reya, and A. Vogt, Eur. Phys. J. **C5** 461 (1998).

[17] L. Whitlow et al., Phys. Lett. **B250** 193 (1990).

[18] J. J. Aubert et al., EM Collab., Phys. Lett. **B160** 417 (1985); M. Arneodo et al., Nucl. Phys. **B321** 541 (1989).

[19] D. Adams et al., SM Collab., Phys. Lett. **B396** 338 (1997); B. Adeva et al., SM Collab., Phys. Lett. **B412** 414 (1997).

[20] A. D. Martin, R. G. Roberts, W. J. Stirling, and R. S. Thorne, Eur. Phys. J. **C4** 463 (1998).

[21] A. E. Dorokov, N. I. Kochelev, and Yu. A. Zubov, Int. J. Mod. Phys. **A8** 603 (1993); A. E. Dorokov and N. I. Kochelev, Phys. Lett. **B304** 167 (1993).

[22] M. Wakamatsu and T. Kubota, Phys. Rev. **D60** 034020 (1999).

[23] S. Hino and S. Kumano, Phys. Rev. **D59** 094026 (1999); *ibid*. **D60** 054018 (1999).